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RATES OF PERFORMANCE LOSS AND NEUROMUSCULAR ACTIVITY IN MEN AND WOMEN DURING CYCLING: EVIDENCE FOR A COMMON METABOLIC BASIS OF MUSCLE FATIGUE

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ABSTRACT

The durations that muscular force and power outputs can be sustained until failure fall predictably on an exponential decline between an individual's 3-s burst maximum to the maximum performance they can sustain aerobically. The exponential time constants describing these rates of performance loss are similar across individuals, suggesting that a common metabolically based mechanism governs muscle fatigue; however, these conclusions come from studies mainly on men. To test whether the same physiological understanding can be applied to women, we compared the performance-duration relationships and neuromuscular activity between seven men [23.3 ± 1.9 (SD) yr] and seven women (21.7 ± 1.8 yr) from multiple exhaustive bouts of cycle ergometry. Each subject performed trials to obtain the peak 3-s power output (P_{max}), the mechanical power at the aerobic maximum (P_{aer}), and 11–14 constant-load bouts eliciting failure between 3 and 300 s. Collectively, men and women performed 180 exhaustive bouts spanning an ~6-fold range of power outputs (118–1116 W) and an ~35-fold range of trial durations (8–283 s). Men generated 66% greater P_{max} (956 ± 109 W vs. 632 ± 74 W) and 68% greater P_{aer} (310 ± 47 W vs. 212 ± 15 W) than women. However, the metabolically based time constants describing the time course of performance loss were similar between men (0.020 ± 0.003/s) and women (0.021 ± 0.003/s). Additionally, the fatigue-induced increases in neuromuscular activity did not differ between the sexes when compared relative to the pedal forces at P_{aer}. These data suggest that muscle fatigue during short-duration dynamic exercise has a common metabolically based mechanism determined by the extent that ATP is resynthesized by anaerobic metabolism.

NEW & NOTEWORTHY Although men and women differed considerably in their absolute cycling performances, there was no sex difference in the metabolically based exponential time constant that described the performance-duration relationship. Similarly, the fatigue-induced increases in neuromuscular activity were not different between the sexes when compared from a metabolic perspective. These data suggest that men and women have similar rate-limiting mechanisms for short-duration dynamic exercise that are determined by the extent the exercise is supported by anaerobic metabolism.

Keywords: skeletal muscle, sex differences, performance-duration relationship, metabolism, critical power

When a motor task requires skeletal muscle to work at high-intensities, mechanical power and force outputs become impaired, and failure to sustain the level of performance occurs shortly after the onset of contractile activity.[7,10,20,30,33,36,42,69] In contrast, when tasks are performed at relatively low-intensities, muscle fatigue develops more slowly, and the performance of the task can be sustained for considerably longer durations. This fundamental property of the neuromuscular system is known as the performance-duration relationship, and

for dynamic exercises, such as cycling, running and knee extensions, can be accurately defined by an exponential function with three physiologically based components.[14,62,67,68] The first two components set the upper and lower limits of an individual's performance-duration relationship and are, respectively, *1*) the maximum force or power that can be generated for 3 s or less (F_{max} and P_{max}) and *2*) the upper level of force or power that can be supported primarily by aerobic metabolism (F_{aer} and P_{aer}). Any exercise bout performed between these limits requires a net reliance on anaerobic metabolism (i.e., glycolysis and dephosphorylation of phosphocreatine) and cannot be sustained. The third component is a metabolically based exponential time constant (*k*) that describes the performance-duration relationship for any bout of exercise between the two limits. Studies on both isolated limb and whole body dynamic exercises have found that this time constant is similar between individuals despite considerable differences in their absolute performances.[14,62,67,68] The consistency of this finding across different modes of exercise and experimental conditions suggests that the exponential loss in muscle performance has a common metabolically based mechanism determined by the extent that ATP is resynthesized by anaerobic metabolism.[14,62,67,68] However, this conclusion comes from studies conducted almost exclusively on men and to date has assumed that the same rate-limiting mechanisms determine the performance-duration relationship in women.

There are numerous reports of sex differences in muscle fatigue [for reviews see Refs. 34 and 35] suggesting that the assumption of a common metabolic basis for the performance-duration relationship in both men and women may not be valid. The multiple physiological mechanisms proposed to explain the observed sex differences include, but are not limited to, *1*) a greater proportional area of muscle fibers expressing the type I myosin heavy chain isoform in women,[24,25,35,58,59] *2*) altered skeletal muscle metabolism resulting in less accumulation of blood lactate and by-products of ATP hydrolysis in women,[24,25] *3*) differences in neural drive and motor control strategies between the sexes,[19,47,55] and *4*) decreased mechanical compression of the vasculature resulting in greater blood flow and perfusion of the working muscle in women.[36,38,51] However, the evidence for sex differences in muscle fatigue come primarily from isometric contractions, and the findings from the few studies on dynamic contractions are equivocal with some reporting sex differences in muscle fatigue[12,24,53,70] and others finding no differences.[19,52,57,61] Thus it remains unknown whether similar or different mechanisms are responsible for muscle fatigue during dynamic exercises in men compared with women. In addition, previous studies aimed at answering these questions have compared muscle fatigue between the sexes at a limited number of intensities without knowing where the exercise bouts reside on each individual's performance-duration curve. An important consequence of this approach is that the relative

contribution of ATP generated from anaerobic pathways is not considered. This limitation is due, in large part, to inadequacies in the techniques currently available to accurately quantify the amount of anaerobic energy flux, especially during whole body dynamic exercise. To circumvent this concern, we had men and women perform multiple constant-load bouts of cycling exercise (i.e., 11–14 bouts to failure between P_{max} and P_{aer} for each individual) at a range of intensities that spanned across each individual's nonsustainable performance range and that are known to require a net reliance on anaerobic metabolism.[14,62,67,68]

For constant-load exercises sustained until failure, muscle fatigue is accompanied by the progressive increase in the amplitude of the surface electromyogram (EMG).[23,46,48] This increased EMG activity is due primarily to the recruitment of additional motor units and a change in discharge rate of the active motor units and is a compensatory mechanism used by the nervous system to maintain a constant force output as the muscle fibers become fatigued.[1,2,17,28,48,49] Recent studies on men have found that this fatigue-induced increase in EMG activity is associated with the extent an exercise bout relies on anaerobic metabolism and occurs irrespective of the absolute or relative amount of force generated by the muscle.[13,62] Accordingly, the rates of increased EMG activity are more rapid when exercises are performed in hypoxia compared with normoxia or hyperoxia,[5,44,64] and there is a strong correlation between the changes in EMG activity and tissue oxygenation levels.[7,63] However, it is not yet known whether these compensatory neuromuscular activation patterns differ between men and women during fatiguing dynamic exercise.

Thus the purpose of this study was to compare the performance-duration relationships and the neuromuscular activation patterns between men and women from multiple constant-load bouts of cycling exercise to test whether a common underlying process is responsible for muscle fatigue in both sexes. We hypothesized that although men would generate greater absolute pedal forces and power outputs than women, the metabolically based exponential time constants describing the performance-duration relationship and the time course of muscle fatigue would be similar between the sexes. We also hypothesized that *1*) the onset of the fatigue-induced compensatory increase in EMG activity would be associated with the maximum performance supported primarily by aerobic metabolism for each individual but would occur at a wide range of absolute and relative pedal forces across the sexes, and *2*) the neuromuscular activation patterns would be similar between men and women when compared relative to the maximum performances that could be supported aerobically.

MATERIALS AND METHODS

SUBJECTS

Seven men, 21–26 yr of age (mean ± SD; height 179.5 ± 5.6 cm; weight 78.5 ± 11.2 kg), and seven women, 19–24 yr of age (height 167.8 ± 5.2 cm; weight 61.7 ± 4.6 kg), volunteered to participate in this study and provided their written informed consent. All 14 subjects were moderately to highly fit (Table 1); one female and two male subjects were actively training on the club collegiate triathlon team, one female subject was a former competitive collegiate triathlete, and the remaining 10 subjects participated regularly in resistance and/or endurance exercise. All testing procedures were approved by the local Institutional Review Board and conformed to the principles set forth by the Declaration of Helsinki.

Table 1. Physiological performance characteristics for men and women

	Men		Women	
Variable	**Mean ± SD**	**Range**	**Mean ± SD**	**Range**
$\dot{V}o_{2max}$, ml $O_2 \cdot kg^{-1} \cdot min^{-1}$	54.6 ± 9.5	44.2–71.6	44.7 ± 5.6*	40.9–56.4
P_{aer}, W	310 ± 47	250–370	212 ± 15*	188–234
F_{aer}, N	223 ± 33	181–267	153 ± 11*	137–168
Critical power, W	270 ± 57	182–342	188 ± 19*	158–211
P_{max}, W	956 ± 109	848–1116	632 ± 74*	528–757
F_{max}, N	686 ± 74	616–797	456 ± 53*	380–543

The aerobic maximums were the greatest pedal force (F_{aer}) and power output (P_{aer}) that could be sustained for 5 min while eliciting the maximum rates of O_2 uptake ($\dot{V}o_{2max}$). Critical power was the average power output over the final 30 s from the all-out 3-min test, and the mechanical maximums were the greatest pedal force (F_{max}) and power output (P_{max}) that could be sustained for 3 s.

*Significantly different from men ($P < 0.05$).

EXPERIMENTAL PROTOCOL

To obtain the full range of muscular force and power outputs of the performance-duration relationship, subjects completed a minimum of four testing sessions separated by at least 48 h of rest as described previously.[68] Briefly, during the first session subjects underwent a progressive, power-incremented discontinuous cycling test to determine the mechanical power (P_{aer}) and pedal force (F_{aer}) eliciting the individual-specific maximum rate of oxygen uptake ($\dot{V}o_{2max}$). In the

second and third sessions, subjects performed five randomly administered constant-load cycling bouts per session at loads selected to elicit failure between 3 and 300 s. Within these sessions, subjects were required to take a minimum of 15 min of rest between trials but were allowed to take as much rest as they deemed necessary to be fully recovered before the commencement of a subsequent trial. The self-selected rest durations between trials were 19.7 ± 4.2 (SD) min for the men and 20.1 ± 4.5 min for the women (P = 0.58). These rest durations were approximately twofold greater than the 7–10 min rest durations used previously to recover both the mechanical work capacity[60] and the intramuscular metabolites[18] to near pretrial levels following high-intensity fatiguing bouts of dynamic exercise. In the fourth session, subjects underwent a progressive, power-incremented discontinuous cycling test to determine the individual-specific peak mechanical power (P_{max}) and pedal force (F_{max}) attained in 3 s, followed by one to four additional bouts selected to elicit failure between 3 and 300 s to ensure a complete performance-duration curve was obtained. Either at the end of the fourth session or during a fifth session, subjects performed an all-out 3-min test at a predetermined torque load to estimate their critical power.[65] All sessions, other than the first session, began with a standardized 5-min warm-up (men = 125 W; women = 100 W).

MEASUREMENTS

PEDAL FORCE AND MECHANICAL POWER OUTPUT.

All tests were conducted on a stationary, electronically braked cycle ergometer (Velotron, RacerMate, Seattle, WA) equipped with an 85-tooth front sprocket to accommodate the wide range of mechanical power and force outputs between men and women. The ergometer saddle and handlebars were adjusted for comfort at the beginning of the first session and replicated for all subsequent testing sessions. Subjects were secured to the saddle with an adjustable nylon strap and to the pedals with toe clips or pedal straps. The nylon strap ensured subjects remained seated throughout the course of a trial but did not impair leg movement (shown in Fig. 1). Because power is a function of force and velocity, all trials, excluding the all-out 3-min test, were performed at a constant cadence of 80 ± 3 rpm. This ensured that the changes in power output occurred from the differences in the applied pedal forces and not to the more complicated scenario of altering both contractile force and shortening velocity.

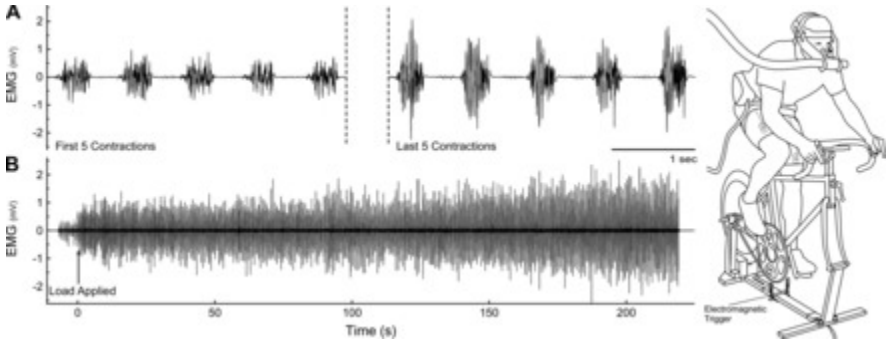

Fig. 1. Representative EMG data from the vastus lateralis of a male subject during a constant-load fatiguing trial that elicited failure in 216 s. The amplitude of the EMG was greater at the end compared with the beginning of the trial (*A*) and increased continuously throughout the bout until the point of failure (*B*). Trials began with 5–10 s of unloaded pedal revolutions to obtain a cadence of 80 rpm before the constant load was applied to the ergometer's flywheel (*B*). The electromagnetic triggers mounted at the base of the pedals ensured that the amplitude of the contraction-by-contraction EMG was computed over the same portion of the pedal revolution.

To eliminate the inertial effects of the 25 kg flywheel and maintain a constant work rate throughout a trial, the flywheel was accelerated to 80 rpm before the commencement of each trial. Trials were initiated with ~5 s of unloaded pedal revolutions before the constant programmed torque load (Wingate Software, RacerMate, Seattle, WA) was applied to the ergometer's flywheel (Fig. 1). Continuous feedback of power output and cadence were displayed on a TV monitor mounted directly in front of the subject and recorded at a sampling frequency of 10 Hz to the ergometer PC. Average pedal forces applied (F_{avg}) per revolution were calculated from the recorded power outputs in accordance with:

$$F_{avg} = \frac{Power}{2\pi fr} \quad (1)$$

where *f* is the pedal frequency in revolutions per second and *r* is the length of the pedal crank arm (165 mm). The reported measures of pedal force and power throughout the manuscript are the average from all of the muscle contractions performed within a particular trial.

$\dot{V}O_2$, P_{AER}, AND F_{AER}.

Volumes of expired gas and concentrations of O_2 and CO_2 were measured continuously throughout each trial with a computerized metabolic system (TrueOne 2400, Parvo Medics, Sandy, UT). Subjects wore a nose clip to prevent breathing through the nares, and expired gases were directed to a 4-liter mixing

chamber via a nonrebreathing valve connected to a 3.05-m corrugated tube with a 1.9-cm radius. This configuration resulted in ~7.5 liters of equipment dead space. Volumes of expired gas were measured at the inlet of the mixing chamber with a heated pneumotachometer (Model 3813, Hans Rudolph, Shawnee, KS), and aliquots of expired air were drawn continuously from the mixing chamber into the system's paramagnetic O_2 and infrared CO_2 analyzers. The analog signals were digitized at 100 Hz with the system's analog-to-digital (A/D) converter and configured to report pulmonary gas exchange measures in 6-s averages. Immediately before each testing session, the metabolic system's analyzers were calibrated with ambient air, a gas mixture of known O_2 (16.01%) and CO_2 (4.99%) concentrations, and a 3-liter calibration syringe. The validity of this system to measure pulmonary gas exchange has been reported in detail elsewhere.[6]

During the first testing session, subjects completed a power-incremented, discontinuous cycling test that consisted of 5-min constant work rate cycling bouts interspersed with at least 3 min of rest or until the subject indicated they were ready to resume testing. The initial power output was 150 W for men and 90 W for women and increased by 30 W for each subsequent trial until the subject was unable to sustain the work rate for the entire 5-min duration despite putting forth their maximal effort. During a subsequent session, subjects performed a trial at a power output midway between the highest power output completed for the entire 5 min and the power output of the last trial in the first session, which the subject was unable to complete. This trial was performed to ensure that the reported values for P_{aer} were within 15 W of the actual performances that could be sustained for an entire 5-min duration. Each individual's $\dot{V}o_{2max}$ was determined as the highest 30-s average obtained from the trial with the greatest power output sustained for 5 min. The average pedal force and power output achieved during the bout eliciting the $\dot{V}o_{2max}$ were considered F_{aer} and P_{aer}, respectively.

PERFORMANCE-DURATION RELATIONSHIP ABOVE P_{AER}.

The exponential performance-duration relationships were obtained from the randomly administered constant-load exhaustive cycling bouts performed at intensities between 100 and 400% of each individual's P_{aer}. These intensities were selected because we knew a priori that they should elicit failure between 3 and 300 s.[68] Subjects completed between 11 and 14 constant-load exhaustive cycling bouts dispersed over three testing sessions and were instructed to maintain a cadence of 80 rpm throughout each trial by using the visual feedback from the TV monitor. Subjects were exhorted to restore their cadence when it fell below 80 rpm, and tests were terminated when the subject's cadence dropped below this level for greater than 3 s despite putting forth their maximal effort. The trial

duration, or time to failure, was immediately recorded and verified post hoc by the cadence records stored in the ergometer PC.

P_{MAX} AND F_{MAX}.

During the fourth testing session, subjects completed a discontinuous power-incremented test to obtain P_{max} and F_{max}. Subjects were required to sustain the constant load at the imposed 80-rpm cadence for 3 s; the greatest pedal force and mechanical power output sustained for 3 s were considered the individual-specific F_{max} and P_{max}, respectively.

ALL-OUT 3-MIN TEST TO ESTIMATE CRITICAL POWER.

Because P_{aer} provides a slight overestimate of the lower limit of the nonsustainable performance range,[31,45] subjects also completed an all-out 3-min cycling test at the end of the fourth session or during an additional session to obtain a more precise estimate of the greatest power output that can be sustained without the progressive accumulation of metabolic by-products (e.g., ADP, H^+, and P_i), i.e., critical power.[41] The resistance for the all-out bout was set at a torque load halfway between the pedal torque at the ventilatory threshold and the $\dot{V}o_{2max}$ (modified from Refs. 15 and 65). Because we employed a discontinuous power-incremented test to obtain $\dot{V}o_{2max}$ instead of a progressive ramp protocol, the V-slope method to estimate the gas exchange threshold[8] was not used. Two observations suggest the slight modification to the all-out 3-min test still provided an accurate estimate of critical power: *1*) the power output reached a steady level during the last 30 s that was at a level below P_{aer} (Fig. 2) but above the ventilatory threshold, and *2*) the highest 30-s O_2 uptake ($\dot{V}o_2$) from the discontinuous power-incremented test did not differ from highest 30-s $\dot{V}o_2$ from the all-out 3-min test (see results). The all-out 3-min trial was initiated with 20 s of unloaded pedaling to increase the cadence to 110–120 rpm before the torque load was applied to the flywheel. Subjects were instructed to attain their greatest pedal cadence as quickly as possible from the beginning of the test and exhorted to pedal as fast as possible throughout the entire 3-min duration. In an attempt to prevent pacing, subjects were blinded to their performance and the elapsed time. Critical power was calculated as the average power output over the final 30 s of the test,[65] and peak $\dot{V}o_2$ was the greatest 30-s average obtained during the all-out bout.

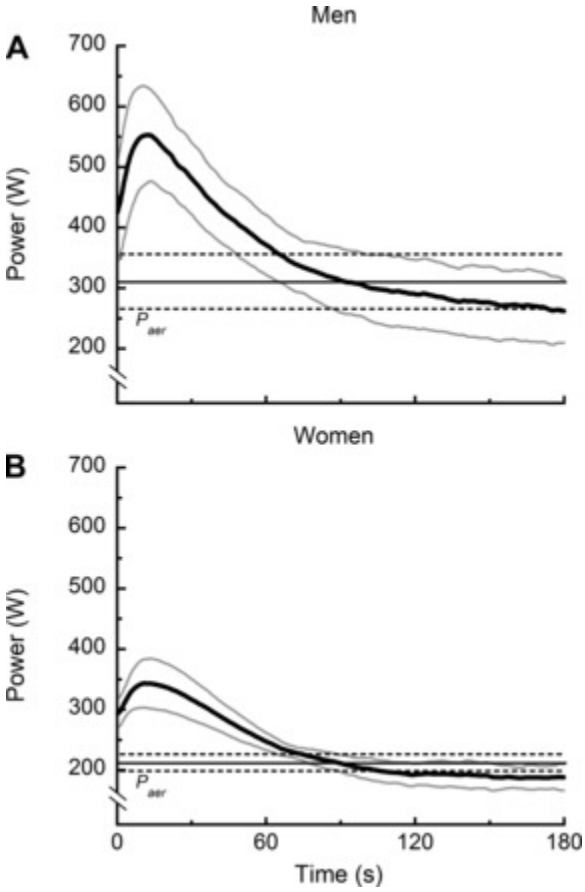

Fig. 2. Mean power profiles for men (*A*) and women (*B*) during the all-out 3-min test to estimate critical power. The power output at the end of the all-out 3-min test fell to similar relative intensities below the highest power output that could be sustained for 5 min and elicited the $\dot{V}O_{2max}$ (P_{aer}; demarked by horizontal black lines) in both sexes. Note the similar profiles for the men and women despite the markedly greater power outputs achieved by the men. Gray solid lines and dashed horizontal black lines represent ±1 SD.

ELECTROMYOGRAPHY.

Surface electromyography (EMG) electrodes were adhered to the skin in a bipolar arrangement overlying the distal portions of the muscle bellies of the right and left vastus lateralis and vastus medialis with an interelectrode distance of ~35 mm. The reference electrode was placed over the superior aspect of the iliac crest. Interelectrode impedance was reduced to below 3 kΩ by shaving and cleaning the skin with ethanol. The locations of the electrodes were marked with indelible ink at the end of each testing session to achieve repeatable electrode placement between sessions. EMG lead wires and electrodes were wrapped with an elastic bandage to secure their placement and maintain quality surface contact during the course of the cycling bouts. Analog EMG signals were amplified (×5,000), filtered (10–1,000 Hz half-amplitude band pass and 60-Hz notch filter; P511, Grass Technologies, Warwick, RI), and digitized at 3,003 Hz with an A/D converter (Digidata 1440, Molecular Devices, Sunnyvale, CA) throughout the duration of each cycling trial.

The digitized signals were stored to a PC and analyzed with a custom analysis routine (IGOR 6.2, Wavemetrics, Portland, OR). Stored EMG data were rectified and averaged (AEMG) on a per contraction basis; an electromagnetic pulse that triggered at the top and bottom of each pedal revolution (shown in Fig. 1) was used to indicate the respective beginning and end of the muscle contraction for the EMG computations. Changes in the amplitude of the AEMG during each constant-load trial >20 s in duration were determined by the slope of the least squares regression line (ΔAEMG/ΔTime).

RATES OF MUSCLE PERFORMANCE LOSS AND THE TIME COURSE OF MUSCLE FATIGUE.

Multiple mathematical models exist to quantify the performance-duration relationship, each with different limitations. Specifically, the two- and three-parameter hyperbolic functions provide the most accurate estimate of the greatest intensity that can be sustained while maintaining a metabolic steady state but provide an overestimate of P_{max} and are relatively inaccurate at describing performances eliciting failure in 2–3 min or less.[31,40,45] In contrast, exponential functions typically overestimate the lower limit of the nonsustainable performance range (e.g., Fig. 2) but are the most accurate method to describe short-duration efforts eliciting failure between 3 s and roughly 15 min.[14,31,33,45] Therefore, to compare the time course of muscle fatigue between the men and women, we used a previously described exponential function[68] and calculated the time constants describing the relationship between the mechanical power (k_p) and pedal force (k_f) and the times to failure for the 11–14 constant-load cycling bouts performed above P_{aer} (e.g., Fig. 3). These computations required a residual minimizing iterative procedure (Kaleidagraph version 4.03, Synergy software, Reading, PA) to solve for the exponential time constants (k_p and k_f) based on the measured terms in the following equations:

$$P(t) = P_{aer} + (P_{max} - P_{aer})e^{-kt} \quad (2)$$

$$F(t) = F_{aer} + (F_{max} - F_{aer})e^{-kt} \quad (3)$$

where $P(t)$ and $F(t)$ are the respective measures of mechanical power and pedal force for the 11–14 constant-load trials with times to failure of duration t, and P_{max}, F_{max}, P_{aer}, and F_{aer} are, respectively, the peak mechanical power and pedal force that could be achieved for 3 s and the greatest mechanical power and pedal force that could be sustained for 5 min while eliciting the $\dot{V}o_{2max}$.

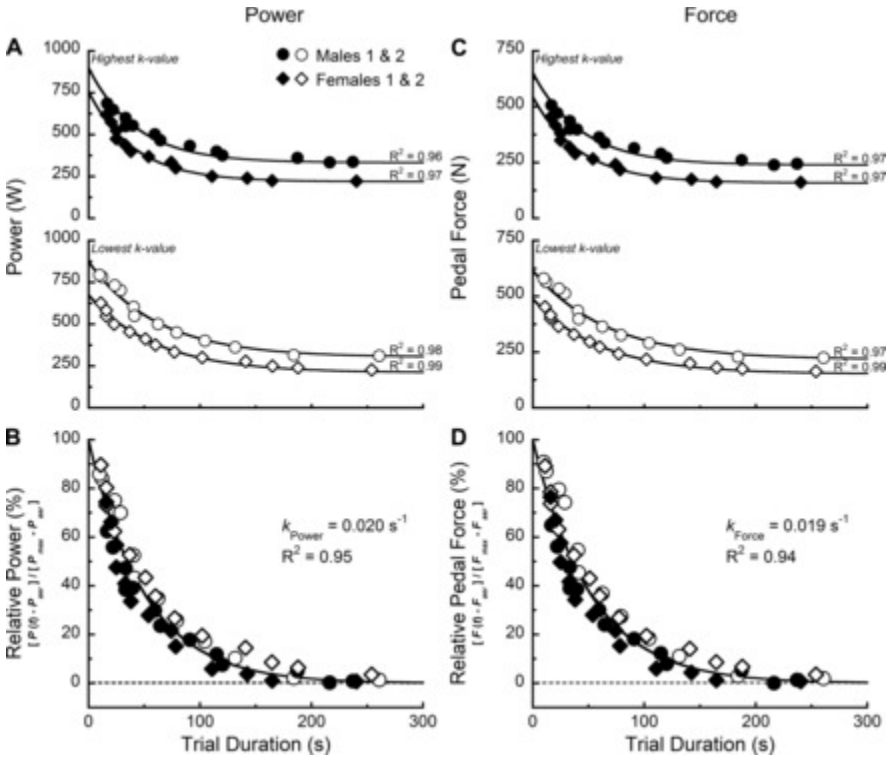

Fig. 3. Individual performance-duration relationships for mechanical power (*A*) and pedal force (*C*) in relation to the times to failure from the male and female subjects with the most rapid (● and ◆) and slowest (○ and ◇) rates of muscle performance loss (*k*). Measured values of P_{max}, P_{aer}, F_{max}, and F_{aer} were used to fit the individual curves in accordance with *Eqs. 2* and *3*. When the absolute performance-duration relationships were expressed as a percentage of the nonsustainable performance range (e^{-kt}), the time course of the relative loss in power (*B*) and force (*D*) for the four subjects were accurately described by a single exponential time constant.

STATISTICS.

Mean differences for all physiological variables were compared between men and women with an unpaired independent samples *t*-test. Assumptions for the homogeneity of variance were tested by using the Levene's test before any statistical comparisons. The a priori level of significance for the *t*-tests was set at $P < 0.05$. Data throughout the manuscript and within the figures are presented as means ± SD.

RESULTS

Maximum Rates of O_2 Uptake, Critical Power, and Peak Sustainable Power and Pedal Force

The average mechanical power output sustained for 5 min while eliciting the Vo_{2max} (P_{aer}) was 68% greater for the men (310 ± 46.5 W) than the women

(212 ± 15.2 W) (Fig. 4 and Table 1; $P < 0.001$). These power outputs were achieved with greater pedal forces (men 223 ± 33.3 N; women 153 ± 11.2 N) (Fig. 4; $P < 0.001$) and elicited a greater $\dot{V}O_{2max}$ in the men (54.6 ± 9.46 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) compared with the women (44.7 ± 5.64 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$) (Table 1; $P = 0.03$). When expressed as absolute rates of O_2 uptake, the values were 4.77 ± 0.27 liters O_2/min (range = 3.70–5.77 liters O_2/min) for the men and 3.16 ± 0.09 liters O_2/min (range = 2.77–3.45 liters O_2/min) for the women ($P < 0.001$). However, the mean respiratory exchange ratio attained during P_{aer} did not differ between the sexes ($P = 0.33$) and was 1.13 ± 0.06 for the men and 1.16 ± 0.04 for the women.

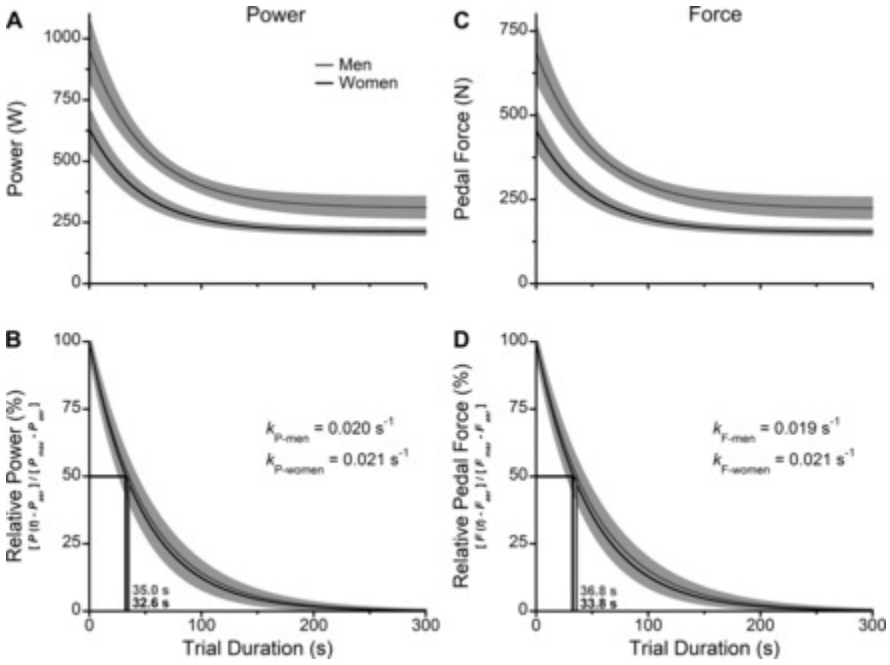

Fig. 4.Study means for the absolute levels of mechanical power (*A*) and pedal force (*C*) produced by the men and women in relation to the durations these performances could be sustained until failure. While the mean absolute cycling performances were markedly greater in the men compared with the women (*A* and *C*), the time constants (*k*) describing the relationship between the relative power (*B*) and force (*D*) and the times to failure were the same for both sexes ($P > 0.05$). For example, the mechanical power (*B*) and pedal forces (*D*) at 50% of the nonsustainable performance range were maintained for similar durations before failure in men and women ($P > 0.05$). Shaded gray regions represent ±1 SD.

Critical power, determined as the average power output over the last 30 s of the all-out 3-min cycling test, was also greater for the men (270 ± 57.4 W) than the women (188 ± 19.2 W) (Table 1; $P = 0.004$). These power outputs, however, were achieved with a similar average cadence over the last 30 s of the all-out bout (men 77 ± 6.3 rpm; women 81 ± 9.8 rpm; $P = 0.41$) and at similar relative

intensities of P_{aer} for both sexes (men 86 ± 7.3%; women 89 ± 6.8%) (Fig. 2; P = 0.55). In addition, the $\dot{V}O_{2max}$ elicited during the all-out critical power test did not differ from the $\dot{V}O_{2max}$ obtained from P_{aer} for either the men (52.8 ± 8.15 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$; P = 0.11) or the women (44.7 ± 4.08 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$; P = 0.96). The highest 30-s mean respiratory exchange ratio obtained during the all-out 3-min test also did not differ between the men (1.36 ± 0.05) and the women (1.32 ± 0.04; P = 0.41).

Peak Mechanical Power and Pedal Force

The burst mechanical power outputs attained for 3 s at 80 rpm was 66% greater for the men (956 ± 108.8 W) than the women (632 ± 74.0 W) (Fig. 4 and Table 1; P < 0.001) and were achieved with greater pedal forces (men 686 ± 74.3 N; women 456 ± 53.3 N) (Fig. 4; P < 0.001). However, when the power outputs were expressed as a multiple of the performances eliciting the $\dot{V}O_{2max}$, both men and women could produce power outputs that were approximately threefold greater than their respective P_{aer} (men 3.1 ± 0.6X, range = 2.4–4.1X; women 3.0 ± 0.4X, range = 2.5–3.5X; P = 0.60). Similarly, if the power outputs eliciting the $\dot{V}O_{2max}$ were expressed as a percentage of the burst mechanical power outputs, both men and women could produce power outputs at this metabolic transition that were ~33% of their respective P_{max} (men 33 ± 5.5%, range = 24–41%; women 34 ± 5.2%, range = 29–40%; P = 0.64). These performances resulted in an average absolute nonsustainable performance range (P_{max}-P_{aer}) that was 65% greater in the men (647 ± 112.4 W, range = 534–845 W) compared with the women (420 ± 78.3 W, range = 316–538 W; P < 0.001).

Performance-Duration Relationship and the Time Course of Muscle Fatigue

In total, 180 exhaustive cycling trials were performed that elicited failure between 3 and 300 s (men = 90 and women = 90). The time constants that best described the exponential relationship (*Eqs. 2* and *3*) between the measured mechanical performances and times to failure for each individual's 11–14 constant-load trials were used to compare the time course of muscle fatigue between the sexes (Fig. 3 and and4).[4] For all of the subjects, the individual force- and power-duration relationships (e.g., Fig. 3) were well described by the calculated exponential time constants with a respective mean R^2 of 0.98 ± 0.01 (range = 0.97–0.99) and 0.98 ± 0.01 (range = 0.96–0.99) for the men and 0.98 ± 0.01 (range = 0.96–0.99) and 0.98 ± 0.01 (range = 0.96–0.99) for the women.

Despite greater absolute neuromuscular force and power outputs in the men compared with the women, the exponential time constants describing the time course of muscle fatigue were similar between the sexes for both pedal force ($k_{f\text{-men}}$ 0.019 ± 0.003/s: $k_{f\text{-women}}$ 0.021 ± 0.003/s) (Fig. 4; P = 0.26) and power output ($k_{p\text{-men}}$ 0.020 ± 0.003/s: $k_{p\text{-women}}$ 0.021 ± 0.003/s) (Fig. 4; P = 0.34). When the analysis was limited to include the men and women with the highest and lowest k-values only, a single exponential time constant (men and women combined) was able to describe the force- and power-duration relationships with an R^2 of 0.94 and 0.95, respectively (Fig. 3). Because the rates of performance loss were not different between the sexes, we derived a single exponential time constant that best described the performance-duration relationships for all 14 subjects (Fig. 5). By using all 180 exhaustive trials from both the men and women, the power- and force-duration relationships were accurately described by a single exponential time constant of 0.0207/s (R^2 = 0.96) and 0.0201/s (R^2 = 0.96), respectively.

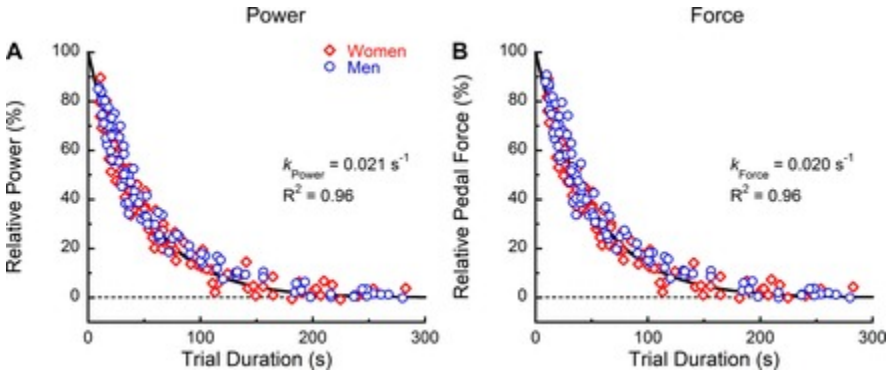

Fig. 5.The time course of the relative loss in power (*A*) and pedal force (*B*) from the 180 exhaustive trials (men = 90 and women = 90) performed by all 14 subjects were accurately described by a single exponential time constant. The time constants for the power- and force-duration relationships were 0.0207/s (R^2 = 0.96) and 0.0201/s (R^2 = 0.96), respectively.

Neuromuscular Activation Patterns and EMG Activity

To compare the neuromuscular activation patterns between the men and women, AEMG activity was quantified contraction-by-contraction for each muscle from a total of 55,646 contractions from the men and 50,756 contractions from the women. In the trials where the power output and pedal forces could be sustained by using primarily aerobic metabolism, AEMG remained essentially constant throughout the exercise bouts in all four muscles (Fig. 6 and and7).[7] In contrast, in the exhaustive trials performed with power outputs and pedal forces that exceeded the maximum performance that could be supported aerobically (P_{aer} and F_{aer}, respectively), and thus required a net reliance on anaerobic metabolism, AEMG increased continuously throughout each constant-load bout until the point of

failure (Fig. 6). The rates of change in AEMG activity (ΔAEMG/ΔTime) during the exhaustive constant-load bouts were typically the highest when the power and force outputs exceeded the performances that could be supported aerobically by the greatest extent (Fig. 7 and and8).[8] When the rate of change in AEMG activity from all trials were plotted against the constant-load pedal forces expressed as a percentage of F_{aer}, the neuromuscular activation patterns were indistinguishable between the sexes (Fig. 8).

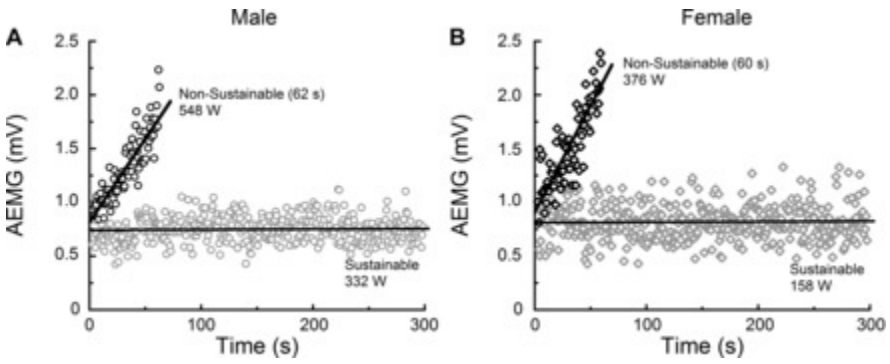

Fig. 6.Contraction-by-contraction, rectified, and averaged EMG (AEMG) from the vastus medialis of the right leg during two constant-load trials for a representative male (*A*) and female (*B*) subject. In the constant-load trials that were sustainable and supported primarily by aerobic metabolism (gray outlined symbols), there was no increase in the amplitude of the AEMG; however, in the constant-load trials that elicited failure in <300 s, the amplitude of the AEMG progressively increased until the point of failure (black outlined symbols). The sustainable trials depicted for both individuals were performed at the same power output as the critical power determined by the all-out 3-min test.

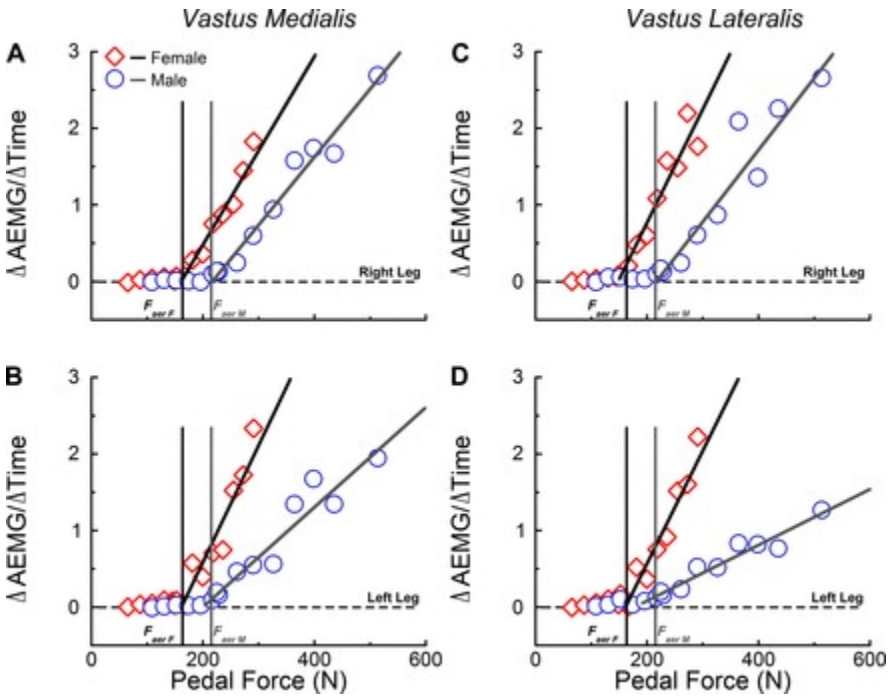

Fig. 7.Rates of change in EMG activity (ΔAEMG/ΔTime) from the vastus medialis (*A* and *B*) and lateralis (*C* and *D*) of both legs for a representative male and female subject in all trials >20 s. In the constant-load trials performed with pedal forces below the maximum forces sustained primarily by aerobic metabolism (force < F_{aer}), EMG activity from all four quadriceps muscles remained essentially constant for both subjects, i.e., ΔAEMG/ΔTime ≈ 0. In contrast, the trials with force outputs that exceeded F_{aer}, and thus required a continued reliance on anaerobic metabolism, AEMG increased in all four muscles for the male and female subject, i.e., ΔAEMG/ΔTime > 0. Linear regression lines for both subjects indicate that more rapid rates of increased EMG activity occurred in trials where the force output exceeded F_{aer} by a greater extent.

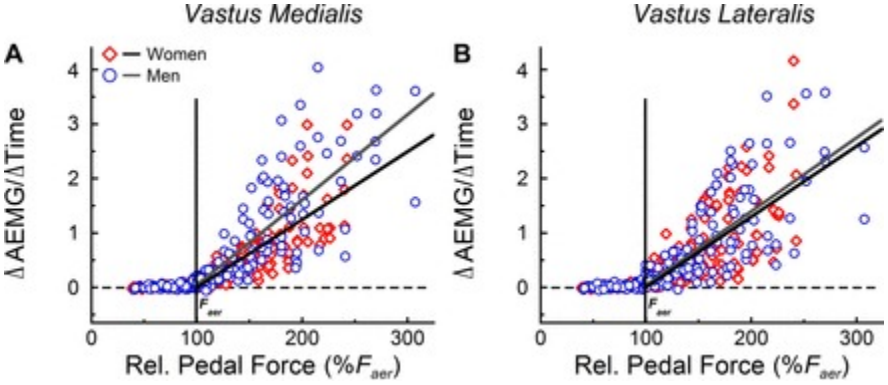

Fig. 8.Rates of change in EMG activity (ΔAEMG/ΔTime) from the vastus medialis (*A*) and lateralis (*B*) of both legs for all subjects and all trials plotted against the pedal force expressed as a percentage of F_{aer}. In constant-load trials performed with pedal forces below F_{aer}, EMG activity from all four quadriceps muscles remained essentially constant; however, in the constant-load trials with force outputs that exceeded F_{aer}, and thus required a continued reliance on anaerobic metabolism, rates of AEMG increased similarly in both muscle groups for the men and the women ($P > 0.05$ for both muscle groups).

DISCUSSION

From the 180 exhaustive trials eliciting failure between 3 and 300 s and the 88 trials performed at or below the maximum performances supported primarily by aerobic metabolism, we found support for each of our hypotheses. As predicted, men were able to generate greater force and power outputs than women across the entire nonsustainable performance range (Table 1 and Fig. 4). Despite the large sex differences in absolute neuromuscular performance, the metabolically based exponential time constants that described the time course of muscle fatigue were similar between men and women (Fig. 4 and and5).[5] In addition, the onset of the fatigue-induced increased EMG activity was closely associated with the metabolic transition where performances could be supported aerobically to those that required a progressive reliance on anaerobic energy pathways to resynthesize ATP (Figs. 7 and and8).[8] The absolute force and power outputs at this metabolic transition were an average of ~68% greater in the men compared with the

women; however, when the constant-load trials were expressed as a percentage of the upper level of performance that could be supported aerobically (F_{aer}), the compensatory neuromuscular activity was similar between the sexes (Fig. 8). These data suggest that a common metabolically based mechanism determines the rates of force and power loss during short-duration nonsustainable dynamic exercise, and that the rate-limiting mechanisms are similar for both men and women. The findings are particularly novel because they apply to the entire nonsustainable performance range, which for the cycling exercise studied here represented ~67% of each individual's entire range of force and power generating capabilities.

Time Course of Muscle Performance Loss and the Development of Fatigue during Short-duration Nonsustainable Exercise

The men and women in this study completed exhaustive trials eliciting failure with over a 35-fold range of trial durations (8–283 s) and generated a 2-fold range in both the peak mechanical performance (P_{max} and F_{max}) and the highest performance that could be sustained primarily by aerobic metabolism (P_{aer} and F_{aer}) (Fig. 4). In addition, the maximum absolute rates of oxygen uptake spanned greater than a twofold range across the sexes (2.77–5.77 liters O_2/min). The physiological differences between the men and women that are necessary to achieve this wide range of performances provided a compelling scenario to test our hypothesis that a common underlying mechanism determines the rates of muscle force and power loss during short-duration dynamic exercise. Despite the wide range of absolute performances, the data support our hypothesis by revealing that a single metabolically based exponential time constant was able to describe 96% of the variance between the level of muscular force or power produced and the duration the exhaustive performances could be sustained until failure for both men and women (Fig. 5). Even when we restricted our analysis to include only the two men and women with the highest and lowest rates of muscle performance loss (Fig. 3), a single exponential time constant was still able to describe the force- (R^2 = 0.94) and power-duration relationships (R^2 = 0.95). This observation prompts the following question: What is the common underlying mechanism that governs the highly predictable performance-duration relationship during short-duration nonsustainable dynamic exercise?

Numerous studies have suggested that the lower physiological limit for nonsustainable exercise is determined by the highest performance that can be supported by aerobic metabolism while still being able to achieve a metabolic steady state.[20,40,54] Direct measures of intramuscular bioenergetics via phosphorus magnetic resonance spectroscopy (^{31}P-MRS) have consistently shown that exercise

intensities performed above this level result in the precipitous buildup of metabolic by-products that are closely associated with fatigue and continue to accumulate until the point of failure.[18,32,41,66] The further the exercise intensity exceeds this metabolic threshold, the more rapidly the metabolic by-products accumulate within the contracting muscle. In contrast, in exercise intensities performed below this level, ATP resynthesis can be met primarily by oxidative phosphorylation and the metabolic environment is stabilized.[18,41,66] Thus it is most likely that the mechanism determining the exponential performance-duration relationship and the common time course of muscle fatigue is metabolically based.

In the current study, the force and power outputs that could be sustained for 5 min while eliciting the $\dot{V}o_{2max}$ were used as the indicator for this metabolic threshold and were 68% greater in men compared with women (Fig. 4 and Table 1). It should be noted, however, that the precise performance level where this metabolic transition occurs remains an active area of investigation[45] but is likely ~10% lower than the 5-min $\dot{V}o_{2max}$ simplification we used here (Fig. 2) and previously.[14,62,67,68] This 10% difference between the power at $\dot{V}o_{2max}$ and the critical power represented 4 ± 0.6% of the performance range studied from the men and women and did not alter any of the conclusions. We elected to use the more conservative approach, because at present the net flux through anaerobic energy pathways cannot be directly measured during whole body exercise. In contrast, the force and power outputs that exceed the aerobic maximum can be evaluated and unequivocally indicate that a progressive reliance on anaerobic energy is required to support the contractile activity. In addition, our experimental focus was to incorporate performances spanning the entire range possible by the neuromuscular system, with particular emphasis on efforts eliciting failure in less than 2–3 min. These brief efforts experience the greatest decrements in force and power (Figs. 2–5), rely the most on anaerobic metabolism,[56] and are the least studied.

Although we are unable to identify the specific underlying mechanisms determining in vivo muscle fatigue, these data provide strong evidence that the mechanisms during short-duration nonsustainable exercise are similar between men and women (Figs. 5 and and8).[8] We posit that the performance-duration relationship and the rate of fatigue development are determined by the extent that the ATP resynthesis necessary to support the contractile activity is provided by anaerobic energy sources. The accumulation of metabolic by-products, particularly inorganic phosphate (P_i) and hydrogen ions (H^+),[21] that occurs from relying on anaerobic metabolism influence exercise performance either indirectly via activation of sensory afferent feedback to the central nervous system[4,11] or directly by impairing key steps in excitation-contraction coupling and the cross-bridge

cycle.[3,26,27] Previous studies in men performing exhaustive efforts that elicited failure with relatively similar durations to those in the current study indicated a near complete ability to volitionally activate the knee extensor muscles.[9,39] These studies in conjunction with the current findings suggest that the rapid exponential performance loss is determined primarily by mechanisms originating within the contracting muscle rather than failure within the nervous system. However, limitations in the methods used to identify fatigue-based mechanisms occurring with the nervous system make it difficult to directly evaluate these mechanisms during whole body dynamic exercise. Future studies to advance these techniques will further the understanding of how a reliance on anaerobic metabolism impairs muscle force and power in such a highly predictable and consistent manner for both men and women (Figs. 4 and and5)[5] and across different modes of exercise.[14,62,67,68]

Fatigue-induced Compensatory Activity of the Nervous System

The neuromuscular activation patterns provide additional evidence that muscle fatigue during short-duration dynamic exercise is determined by a common metabolically based mechanism in both men and women. In the constant-load trials that were sustainable and could be supported primarily by aerobic metabolism, we observed minimal increase in the EMG activity of the knee extensor muscles in either the men or women (Figs. 6 and and7).[7] In contrast, when the force and power outputs exceeded the maximum performance that could be supported aerobically, and thus required a progressive reliance on anaerobic metabolism, the EMG activity increased from the beginning of the trial until failure. The rates of increased EMG activity were more rapid the further the power and force outputs exceeded the performance that could be supported aerobically, and this trend was similar for the men and women (Figs. 7 and and8).[8] The close association between the onset of the fatigue-induced increased EMG activity and the maximum performance that could be supported aerobically provide further support that muscle fatigue and the compensatory neuromuscular response are determined by a reliance on anaerobic energy to resynthesize ATP.

The increased EMG activity during constant-load fatiguing exercise is most commonly attributed to an increased motor unit recruitment to compensate for the fatigue occurring within the originally activated fibers.[2,17,48] Altered motor unit discharge rates may also be responsible for the increased EMG activity but are not likely the primary factor, because motor unit discharge rates can either increase, decrease, or display minimal net change during submaximal fatiguing bouts.[1,17,28,29] These conclusions are determined primarily from studies on isometric contractions due to the inherent difficulty of tracking individual motor

unit action potentials during dynamic contractions. However, the limited data that are available suggest that similar motor control strategies to those observed during isometric contractions occur during concentric contractions.[22,29] Thus the increased EMG activity during the exhaustive dynamic contractions in this study was probably due primarily to an increase in motor unit recruitment. Irrespective of the precise motor control strategy, the conclusion that the fatigue-induced increase in EMG activity is determined by the net reliance on anaerobic metabolism and is similar for men and women remains unaffected.

The finding that the onset of the fatigue-induced increased EMG activity is closely associated with the net reliance on anaerobic metabolism supports numerous previous observations from both static and dynamic contractions and from whole body and isolated limb exercises.[13,16,49,62] However, it is not as well recognized that this metabolic transition and the corresponding compensatory neuromuscular response can occur irrespective of the absolute or relative amount of force generated by the muscle.[13,62] This conclusion is supported by closer examination of the data from the men and women in the current study. If the performances eliciting the maximum rates of oxygen uptake (P_{aer} or F_{aer}) are expressed relative to the maximum mechanical performances (P_{max} or F_{max}), which in dynamic contractions is analogous to expressing performances relative to the maximum voluntary contraction, the metabolic transition occurred between 24 and 41% of the maximum mechanical performances across the men and women. Similarly, the absolute pedal forces and power outputs at this metabolic transition spanned a range of 137 to 267 N and 188 to 370 W, respectively. The variations in the force and power outputs at which this metabolic transition occurs within a mode of exercise are likely explained by the multitude of physiological factors known to affect the maximum aerobic power that can be generated across different individuals.[43] However, when these differences are accounted for by expressing the neuromuscular activation patterns relative to the maximum performance supported primarily by aerobic metabolism, a clear and consistent trend in neuromuscular activation is observed that occurs similarly in both sexes (Fig. 8). These findings provide novel insight that when greater rates of increased EMG activity occur across individuals or experimental paradigms, the more rapid rates of muscle fatigue can likely be explained by a greater reliance on anaerobic metabolism.

Concluding Remarks

The data here reveal that the exponential performance-duration relationship, originally conceptualized from studies on running, cycling, and knee extension exercises in men.[13,14,33,62,67] can now be extended to an equivalent application and

understanding of the factors responsible for muscle fatigue during dynamic exercise in women. These findings, in conjunction with others,[13,14,33,62,67] offer refinement to the prevailing paradigm that the causes of muscle fatigue across different tasks do not have a common mechanistic basis. Indeed, the mechanisms of fatigue for considerably longer-duration, low-intensity efforts[27] or intricate manipulations to a motor task[37,50] may differ from those presented here. However, the consistency of the exponential decrements in force and power that has been observed across multiple modes of dynamic exercise,[13,14,33,62,67] and that are similar for individuals with different sprint and endurance capabilities[67] and for men and women (Figs. 4 and and5),[5] suggests there is a common physiological basis of muscle fatigue during dynamic exercise. We conclude that muscle fatigue during short-duration nonsustainable dynamic exercise and the corresponding compensatory neuromuscular activity are determined by a net reliance on anaerobic metabolism to support the contractile activity.

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AUTHOR CONTRIBUTIONS

C.W.S. performed experiments; C.W.S. analyzed data; C.W.S. and M.W.B. interpreted results of experiments; C.W.S. prepared figures; C.W.S. drafted manuscript; C.W.S., S.K.H., and M.W.B. edited and revised manuscript; C.W.S., S.K.H., and M.W.B. approved final version of manuscript.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

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